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LAW ENFORCEMENT HEAD-BORNE PERSONAL PROTECTIVE EQUIPMENT HEARING ATTENUATION

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14. ABSTRACT
Test methods were developed to quantify and assess the effects of personal protection equipment (PPE) on hearing. The tests use a head and torso simulator that is able to don PPE and employs advanced acoustic, signal processing, and measurement techniques. The tests measure localization and speech intelligibility effects of PPE. The methods also assess the effects of noise generated by PPE fabric and/or electro/mechanical noise. Localization effects are evaluated in terms of the Head-Related Transfer Function (HRTF). Speech intelligibility is evaluated using the Speech Transmission Index (STI). Results show that HRTF and STI scores are significantly altered with various PPE and PPE-created noise.

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Personal protective equipment, Speech intelligibility, Localization, Hearing, Communication

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EXECUTIVE SUMMARY

The goal of the Phase I research was to develop test methods to quantity the effects of personal protection equipment (PPE) on human hearing. The tests can be used to assess the speech intelligibility effects of PPE and PPE created noise, as well as their localization effects. The developed tests incorporate a human head and torso simulator, a computer, professional audio recording and playback equipment, and a turntable system.

A Century Body Opponent Bag (BOB) was purchased for use as the head and torso simulator. This was selected due to the capabilities of the simulator to don PPE such as jackets and APRs. The simulator was modified and equipped with a Nady CM100 microphone in each of the ear canals, thus allowing for a binaural recording to be captured. The BOB was placed on a manual turntable to allow the BOB to be rotated along the azimuth (horizontal direction). Markings were made on the turntable at every 22.5°, thus allowing for the BOB to be rotated to 16 different azimuths.

A sound booth was set up in one of our existing rooms using acoustical foam and wall panels to treat the room, thus minimizing unwanted noise and reflections. The BOB was placed in the sound booth along with a Tannoy DI-5 DC loudspeaker, which was amplified by a Crown D75-A amplifier. The loudspeaker and microphones were connected to a PreSonus DigimaxLT preamp, which was connected a SoundBlaster X-Fi Xtreme sound card.

To test the localization effects of each PPE, an impulse response measurement was taken using the Swept Sine method[*] at each of the 16 azimuths. Analysis of the data was conducted by using in-house developed Matlab scripts. Interaural level and time differences as well as transmission losses were calculated for each of the PPE. The results of the analyses were examined in terms of their psychoacoustic effects on localization.

The speech intelligibility effects of the PPE were assessed in terms of the fabric and mechanical noise generated by the PPE and changes in the Speech Reception Threshold (SRT). Mechanical noises generated by the powered air-purifying respirators were recorded while being donned by the BOB. Fabric noise was recorded by placing a microphone in each ear of an LcT employee while they donned the PPE and performed pre-defined movements at specific speeds. LcT is currently in development of a robotic head and torso simulator that can replace the need for a human subject. Both the PPE created noises were assessed in terms of sound pressure level (SPL) and frequency spectrum. The speech intelligibility effects for each PPE were predicted using the well-known Speech Transmission Index (STI) [**,***].

The developed test methods were shown to analyze the important effects of the PPE on speech intelligibility and localization. A generalized prediction model was also developed, which can be used to predict the effects of PPE with similar designs and material that have not yet been tested. The next step (Phase II) will be to determine the acceptable PPE hearing effects, develop a grading system that can provide users information on the hearing effects of PPE and incorporate our test methods into a standardized test.

*ANSI. *Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters.* ANSI S1.11-2004.

Steeneken, H.J.M.; Houtgast, T. Validation of the revised STIr Method. *Speech Communication* **2002, *38*.

***Steeneken, H.; Houtgast, T. Basics of the STI Measuring Method, Past, Present, and Future of the Speech Transmission Index. *International Symposium on STI*. The Netherlands, October 22-24, 2002.

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PREFACE

The work described in this report was authorized under Contract No. W911NF-07-D-0001. The Task was performed under a Scientific Services Agreement issued by Battelle Chapel Hill Operations, 50101 Governors Drive, Suite 110, Chapel Hill, NC. This work was supported by the Office of Law Enforcement Standards, National Institute of Standards and Technology through the Department of Homeland Security, Science and Technology Directorate, Project No. 8N3YPA, under the auspices of the U.S. Army Research Office Scientific Services Program administered by Battelle (Delivery Order 0309). This work was started in December 2007 and completed in December 2008.

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LAW ENFORCEMENT HEAD-BORNE PERSONAL
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1. INTRODUCTION

The objective of this project is to develop repeatable and quantifiable test methods to determine the effects of Personal Protective Equipment (PPE) on human hearing. These include the speech intelligibility and localization effects that occur while donning PPE. The developed tests are also capable of quantifying the effects of PPE created noise, such as fabric and mechanical noise. These test methods could be used to better assess future PPE systems in terms of hearing and could be used in future Law Enforcement PPE standards.

Objective tests were developed using advanced acoustic, signal processing and measurement techniques to determine the hearing effects a human undergoes, while donning PPE. A head and torso simulator is used, in conjunction with a manual turntable, to measure the attenuation effects of PPE at various azimuths. This is accomplished by taking impulse response measurements at each azimuth and for each PPE (subsystem level) and combination of PPE (system level). These impulse responses describe the Head-Related Transfer Function (HRTF) of the simulator. The HRTF describes, in detail, the acoustical properties of the head, thus allowing for an assessment of the effects of a given PPE on hearing. This assessment allows for the determination of the speech intelligibility and localization effects that can occur, while donning PPE.

Some Air-Purifying Respirators (APRs) are powered by batteries to increase the safety of the user. As a consequence, these powered-APRs (PAPRs) produce electro/mechanical noise, which if loud enough can be detrimental to the hearing abilities of the wearer. Another source of PPE created noise is generated from movement by the wearer. Certain PPE, such as chemical suits and escape hoods, produce fabric noise with movement, thus affecting the wearer's hearing abilities. The developed test methods take into account these PPE created noises by recording the noise generated and assessing the noise characteristics and their effects on speech intelligibility and localization.

During Phase I of this project, test methods were developed to provide quantifiable and repeatable measurements of the hearing effects of PPE. The developed test methods are comprehensive and unlike any other tests developed to measure the attenuation effects of PPE. The Phase II project goal will be to further develop these tests and incorporate them into a standard.

2. IMPORTANCE OF TESTS

Tests that effectively quantify the hearing effects of PPE are essential to ensuring the safety of the wearer. A person wears PPE to protect themselves from chemical, biological, and radioactive substances, however, doing so can affect their communication and localization abilities. These parameters must be evaluated when selecting PPE to be used in combat or law enforcement situations, since they can help determine the safety and success of an operation. There have been few standardized tests developed to assess some of these parameters, but our developed tests have the capability to provide a comprehensive assessment of the hearing effects of PPE. Our developed tests can also lead to the development of a more effective PPE design.

2.1 Importance of Localization and Speech Intelligibility

Localization and speech intelligibility can be of great importance in many situations. Therefore, we must be able to classify in what situations these two parameters are more or less important. It is also important to understand the impact of these parameters and what factors influence them.

2.1.1 Situational Awareness

Situational awareness is the ability of a person to recognize the events that take place in their environment. This includes auditory events, such as a gunshot, speech or footsteps. This also includes the ability to localize sound sources and comprehend speech. Humans have the ability to localize sound in the horizontal plane with great accuracy, within 2° when the sound source is directly in front of them and within 10° when the sound source is to the left/right of them [4, p.41]. Research has shown that when one or both ears become occluded (i.e., by wearing PPE), the localization ability of humans can be reduced significantly. If these abilities are altered, a person may experience diminished situational awareness and not recognize where sounds are being emitted from, thereby increasing the person's chance of injury or fatality. Most research on PPE localization effects has found that the most prominent effect is front-to-back confusions [5, 9, 18, 19]. Thus, if a sound is being emitted from in front of the user, the user may perceive the sound as being emitted from behind them and vice versa. This could be a significant problem for users that rely heavily on sound localization cues (i.e., a soldier trying to identify an enemy location or a police officer trying to locate a criminal in a dark building). This illustrates the importance for donning PPE that has minimal effect on hearing.

2.1.2 Hearing Critical Tasks

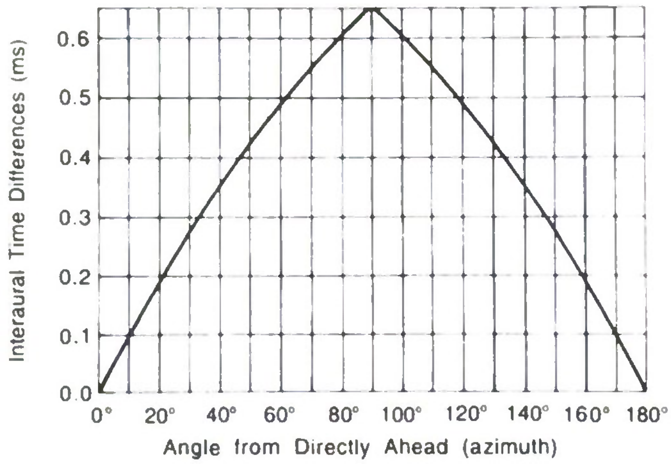
The hearing effects of PPE may be more acceptable in certain scenarios than in others. For example, in a stealth operation the ability to localize quiet sounds, such as a door creak or footsteps, will be more important than for an officer working in crowd control. The chance of injury or fatality in the stealth operation is much greater than in the latter example and therefore requires an unaltered hearing ability. Both of these tasks have important hearing ability requirements and are therefore considered Hearing Critical Tasks (HCTs). As stated, different HCT may require different hearing abilities and performance depending on the situation. This factor must be taken into account when defining the localization and speech intelligibility effects of PPE. To simply grade PPE with a pass/fail will not effectively evaluate the hearing properties of the PPE. Therefore, a grading scale, which takes into account the HCT requirements, is suggested for development during Phase II of this project.

2.1.3 Factors Affecting Localization

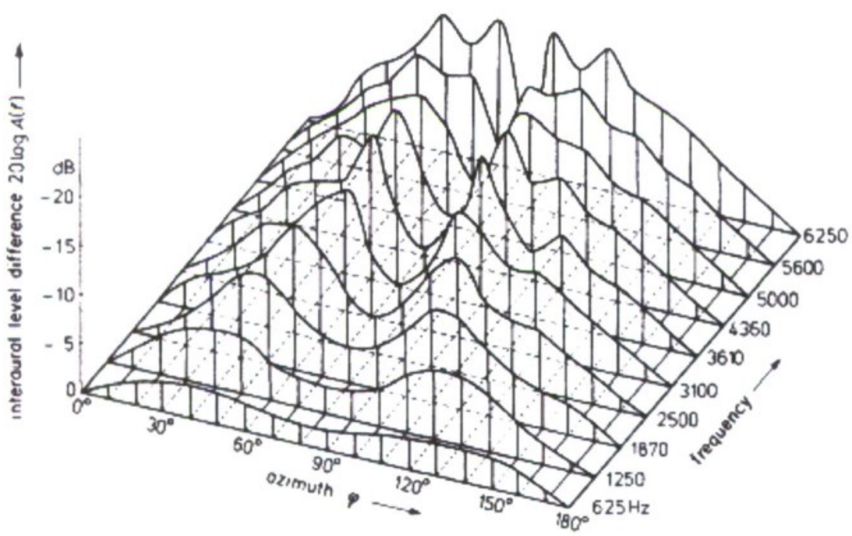
Over the last century, the localization abilities of humans have been studied extensively. There exist three important cues for humans to localize sound sources accurately [4, pp 137-177]. These are the interaural time difference (ITD), interaural level difference (ILD), and spectral cues. The ITD is the difference in arrival times between the two ears. The ILD is the difference in level/intensity between the two ears. The spectral cue describes the frequency content of the sound source, which is shaped by the ear.

When a sound source is located directly in front of a human, the ITD and ILD of the sound is approximately zero since the sound arrives at the same time and level. If the sound source shifts to the left/right, an ITD and ILD occur, which helps humans determine where the

sound is being emitted from. When a sound source is directly to the right/left of the listener the ITD reaches its maximum value, as shown in Figure 1A; however, the same is not true for ILDs as shown in Figure 1B.



A)

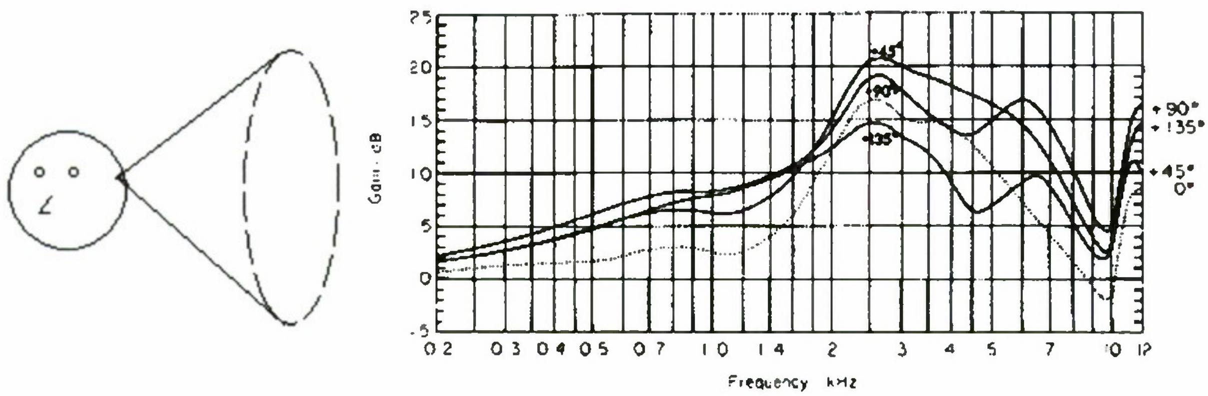


B)

Figure 1. A) The expected ITD of a sound source as a function of azimuth.[20] The ITD does vary with frequency, but not significantly. B) The expected ILD of a sound source as a function of azimuth and frequency. [4, p.73] Actual ITD and ILD will be slightly different, due to the asymmetry of the human head. The ILD and ITD are symmetric about 90° (sound directly to the left/right of listener).

From these graphs we can see that they are generally symmetric about 90° (sound directly to the left/right of listener). The area where the ITD and ILD are equal is referred to as the cone of confusion, see Figure 2A. To distinguish where the sound source is actually being emitted from, humans use the spectral cues of the sound. That is, certain frequencies are either attenuated or accentuated depending on whether they are in front/behind or above/below the listener, as shown in Figure 2B. These spectral cues are important only at high frequencies

above 1 kHz [4, pp.93-116]. To evaluate these parameters, the developed test is designed to measure the ITDs and ILDs as well as the acoustic transmission losses (TLs), which evaluate the spectral changes introduced by the PPE. All of this is accomplished by measuring the HRTF of the head and torso simulator with and without wearing PPE.



A) B)

Figure 2. A) The Cone of Confusion: A sound source coming from any point on the end of the cone (dashed line) will have the same ILD and ITD. To differentiate where the actual sound source is being emitted, humans use the spectral cues that are altered by the ear depending on the sound source location. B) Plot of the frequency spectrum for an ear at different azimuths [14]. The ILD and ITD will be the same for a sound source at 45° and 135°, but from the plot we can see that the shape of the spectrum changes, most noticeably a reduction in frequencies above 2 kHz at 135° (behind the head) .

2.1.4 Factors Affecting Speech Intelligibility

Speech intelligibility can be defined as the ability of a listener to understand speech. The determination of the speech intelligibility of humans has also been extensively studied. The main factor that determines the speech intelligibility of humans is the signal-to-noise ratio (SNR). It is well known that as the SNR increases, so does the speech intelligibility. Thus, the speech intelligibility in a condition where the noise level is the same as the speech level will be diminished compared to a condition where the noise level is 15 decibels (dB) below the speech level. From this we can see that if PPE created noise is loud enough, then the speech intelligibility of the wearer can be greatly diminished.

It is important to note that the SNR with and without PPE will be the same, assuming that no fabric or mechanical noise is being generated, thus in theory the speech intelligibility should remain the same. However, we must take into account the threshold of hearing when assessing speech intelligibility. For instance, the SNR may remain the same, but if the mask attenuates the sound below the threshold of hearing, then we can expect a decrease in the Speech Reception Threshold (SRT).

Speech intelligibility is also dependent on frequency. The most important range of frequencies for comprehending speech is between 125 Hz and 8 kHz [15]; thus, if the frequency content of the noise is above or below these levels they will not have a significant impact on speech intelligibility.

To predict the speech intelligibility while donning PPE, the Speech Transmission Index is used. All of the above mentioned factors that affect speech intelligibility are taken into account by this algorithm.

2.2 Need for Standardized Test

Currently there are only a few standardized speech intelligibility tests and no standardized localization tests for the assessment of PPE. Most of these tests are only tailored to a specific application, such as speech intelligibility in noise or at a constant speech level. Most of these tests also require the use of human subjects, which is costly and time consuming. A standardized localization test for users donning PPE has also not been developed, thus further demonstrating a need for a standardized test. The goal of this project is to develop test methods that can be incorporated into a PPE standard that can effectively quantify the localization and speech intelligibility effects of PPE. Our tests were developed using a head and torso simulator, thus reducing the cost and time of the tests.

As stated, a few standardized tests have been developed and are currently in use for measuring speech intelligibility. For example, the NIOSH MRT test [13] is used to measure the communication ability of a speaker and listener wearing the same PPE. Again, these tests are restrictive in several ways. For one, all of them require the use of human test subjects. This has several effects on the outcome of the test. They are subjective, not repeatable, costly, and time consuming. Some of these tests are also application specific, requiring only certain noise and speech levels.

Our developed test methods provide several benefits over existing methods. First, the tests do not require the use of human test subjects, but rather a head and torso simulator. Secondly, the designed tests can evaluate the localization effects of the PPE. Third, the tests take into account the fabric noise and mechanical noise generated by the PPE. No test to our knowledge incorporates these factors in determining localization and speech intelligibility effects.

2.3 Future Development of PPE

Another goal of these tests is to give insight to PPE manufacturers on the hearing effects of PPE. By doing this, we believe that future PPE designs can be enhanced in terms of hearing ability. The developed tests will allow PPE manufacturers to assess their current PPE and alter their design to increase the localization and communication abilities of the wearer. Thus, more effective PPEs can be designed to aid PPE users during HCTs.

3. DEVELOPED TEST METHODS

The details of the developed test methods are discussed in this section. The equipment needed to conduct the tests and the proper setup and calibration procedures are given. The proper procedure to assess the results after the tests have been conducted is also given.

3.1 Scope

The scope of these tests covers several important aspects of PPE hearing evaluation. The first is the determination of localization effects of the mask. The designed test evaluates several important parameters that determine the localization ability of a human, which are explained in the following sections. The localization ability of the user can also be extended to conditions where PPE created noise or even stationary background noise is also present.

These tests also evaluate the speech intelligibility effects of PPE. As with localization, the speech intelligibility test covers the conditions when PPE created noise (i.e., fabric and mechanical noise) or stationary background noise is present.

The localization and speech intelligibility assessment are capable of covering conditions with varying sound source or speech levels. For example, the tests can evaluate the effects of PPE in understanding speech at whispering levels up to shouting levels. This is important for defining different HCT requirements. Thus, the PPE can be evaluated under specific conditions.

3.2 Equipment

To conduct the developed tests the following equipment is needed:

1. A head and torso simulator that accurately reflects the anthropometric dimensions of a normal human. The simulator must be capable of having a microphone placed in each of its ears, and the ears must be similar to an actual human, with regards to pinnae shape and size. The simulator must also be capable of being placed on a turntable and at a height of no less than 5' measured at the top of the head; this will help minimize acoustic reflections from the floor. For the Phase I, project Li Creative Technologies (LcT) used the Century Body-Opponent-Bag and modified the ears and inside of the head to allow microphones to be placed in them, shown in Figure 3A.

2. A turntable that can be accurately rotated 360° in 22.5° increments. A PC controlled turntable is preferred to reduce human error when rotating the simulator. LcT used a manual turntable and measured the 22.5° increments with the proper measuring equipment.

3. Two microphones with a flat frequency response (±3dB) from 20Hz to 20kHz. The microphones must be small enough to be placed inside the ear canal of the simulator. The same microphone must be used for both ears. Two Nady CM100s, which were modified to fit into the simulator's ear canals, were chosen for this project, shown in Figure 3B.

4. A point source (single cone) loudspeaker with a flat frequency response (±3 dB) from 100 Hz to 20 kHz. The loudspeaker must have a sensitivity rating of at least 85 dB (1 W @1 m), to ensure that the SNR is sufficiently large. A Tannoy Di5-DC was chosen for this project.

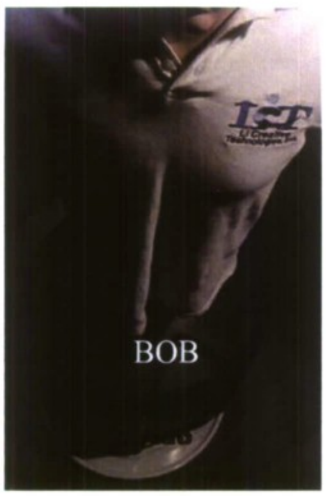
5. A power amplifier, if necessary, for the loudspeaker that meets the recommended power requirements of the loudspeaker. The amplifier must have < 0.1% THD and a flat frequency response (± 0.5 dB) from 20 Hz to 20 kHz. A Crown D-75A was chosen for this project.

6. A high quality sound card that is capable of recording at 44.1 kHz with 16-bit precision. The sound card must be set up to allow for a clean recording (no effects added). The sound card must also be able to record two tracks simultaneously. A SoundBlaster X-Fi Xtreme Audio sound card was used for this project.

7. If the soundcard does not provide the necessary amplification gain necessary to obtain a high SNR recording, then a preamplifier with at least a two channel input/output must be used. The preamp must also have a flat frequency response (± 0.5 dB) from 20 Hz to 20 kHz. If a digital preamp is used, then the preamplifier must be able to synchronize with the sound card and have a sampling rate of at least 44.1 kHz. A PreSonus Digimax LT was used for this project. The analog input/outputs were used.

8. A computer with recording software that allows for two tracks simultaneously recording at a minimum of 44.1 kHz. The software must be able to generate a swept sine signal with a minimum duration of 10 s from 20 Hz to 20 kHz. The computer must be fast enough to handle the playback/recording of the audio recording software. A Dell Dimension E510 with 1 GB of RAM and a 3.0 GHz Pentium 4 processor was used for this project. The Adobe Audition recording software with the Aurora 4 plug-ins was used for all the recordings.

9. A high quality Type II sound level meter capable of measuring sound pressure levels (SPLs) between 30-120 dB. The sound level meter must also provide A and C weighting measurements. A Reed SL-4022 sound level meter was used for this project.



A)

B)

Figure 3. A) The BOB head and torso simulator mounted on a turntable. B) Illustration of the microphone placement in the simulator.

3.3 Attenuation and Localization Test Procedure

To evaluate the attenuation and localization effects of the PPE, the Head-Related Transfer Function (HRTF) is calculated. The HRTF completely describes the ITD, ILD, and TL characteristics of a listener. We can calculate the HRTF when the simulator is not donning PPE and under the condition when the simulator wears PPE. Through this procedure we can determine the changes or transfer function (TF) of the PPE. The TF of the PPE allows us to determine how the PPE alters the important cues for localization.

The HRTF is calculated by obtaining the impulse response of the ear at varying azimuths. To obtain the impulse response, a method developed by Angelo Farina that uses a swept sine signal is used [8]. This method was chosen over other popular methods, such as Maximum Length Sequences, due to its ability to obtain large SNR and immunity to time synchronization. The only drawback of this method is the susceptibility to impulsive noises, such as door slams. In environments where this may be a problem (i.e., busy office buildings), the MLS method may be used instead. We will assume that the Swept Sine method will be used.

The HRTF is calculated using 16 different azimuths. They range from 0° to 337.5° in 22.5° increments. These azimuths were chosen based on symmetry and also because they provide a detailed HRTF with minimal calculations. Common HRTF measurements may measure in 5° increments, but LcT felt that this detailed HRTF is unnecessary and time consuming. The chosen azimuths will provide enough information to effectively evaluate the localization effects of the PPE.

3.3.1 Setup and Calibration

This test requires all the equipment listed in Section 3.2. The setup of the test is as follows:

First, the simulator must be in place on the turntable so that the center of the head will remain in the exact same place while the simulator is rotated. This is to ensure symmetry while rotating the simulator. Thus, a measurement at 22.5° and -22.5° should provide almost identical ILD, ITD, and TL results. Please note that 0° refers to when the simulator is facing the loudspeaker and 90° refers to when one of the simulator's ears is directly facing the loudspeaker.

Next, the loudspeaker must be placed at a distance between 0.5 m to 1 m measured from the front of the loudspeaker to the middle of the simulator's ear, with the simulator at 0°. These distances were chosen because any distance less or greater than this can alter the HRTF significantly and also because these distances allow the test to be conducted in a relatively small amount of space [6]. The center of the loudspeaker's cone must be at the same height of the simulator's ears and the loudspeaker must be placed directly in front of the simulator (center of cone is midway between the ears). The simulator and the loudspeaker should be placed in the geometric center of the room as to maximize the distance between any walls; this will help reduce unwanted acoustical reflections.

Calibration of the audio equipment should be done in the following manner:

First, we must calibrate the loudspeaker to produce the loudest SPL possible without distortion. Turn off all unnecessary equipment that can produce noise (i.e., lights) and

close all doors/windows. Place the simulator at an angle of 0° and remove any PPE from the simulator. Generate a white noise signal with duration of 10 s. Using good gain structure for all the audio equipment (i.e., none of the devices clip), play back the signal at a level that is known not to clip the loudspeaker but louder than 75 dBC, measured with the sound level meter at the ear of the simulator. Set the recording level of the software/preamps so that at this level there is at least 30 dBFS (dB Full Scale) of head room. Make a recording of the white noise signal and plot the frequency spectrum of the signal.

Next, continually increase the output of the loudspeaker in 5 dB increments and record the white noise signal each time and plot the frequency spectrum. Each increment should lead to a 5 dB increase across all frequencies in the frequency spectrum plot. Once any frequency in the spectrum plot of the recording does not increase by 5 dB, then the previous output level should be used.

To calibrate the recording levels, place the PPE to be tested on the simulator and rotate the simulator to 67.5° so that the left ear is pointing towards the loudspeaker. At this angle the loudest recording level will be achieved. Repeatedly play back the signal and turn up the gain on the preamplifier and/or sound card until the maximum recording level, as indicated in the software, reaches -6 dBFS for the left ear recording channel. This will allow for 6 dB of headroom and prevent any clipping of the recorded signal. Again, use good gain structure and make sure that at no point in the recording signal chain any clipping is present. Once this level is found, adjust the right ear recording channel preamp and/or sound card settings to match the left ear channel.

Next, to ensure that the microphones are calibrated correctly, place the simulator at 0° and remove any PPE. At this point the speaker and recording levels should be calibrated. Play back and record the white noise signal. Plot the frequency response of both channels of the recording using a 512-point FFT. The two plots must be within ±3 dB from 100Hz-8 kHz. If this is not the case, recheck the loudspeaker setup and microphone setup.

Once the microphones are calibrated to match each other, none of the settings on any of the audio playback or recording equipment should be changed. The next step is to play back a calibration signal (pink noise) at a 75 dBC SPL measured with the sound level meter at the simulator's ear. The volume of the calibration signal should be changed via the software to match this level, because all the hardware is already calibrated. Once the calibration signal is at 75 dBC, a10 s recording of the signal must be made. The corresponding recording level (in dBFS) should be noted. In this way, if the tests are being conducted at another facility or with different equipment, the attenuation calculations can be compensated for correctly by matching the calibration signal recording levels.

3.3.2 Procedure

To conduct the test, a measurement of the simulator without any PPE must first be made. This is only required once. Afterwards, any PPE or combination of PPE may be measured. Due to the variations in PPE fitting, explained in Section 3.6, any measurement with the simulator donning PPE must be taken at least five times. The PPE must be taken off and put back on for each test. The average of each of the tests will be used to evaluate the PPE.

The test is conducted in the following manner. The loudspeaker must play back a 10 s swept sine signal. After the recording is obtained, the simulator must be rotated to the next position and the impulse response measurement is conducted again. After all the azimuths have

been tested, the procedure is complete. When testing PPE, this procedure must be conducted at least five times. Each time the PPE must be taken off and refitted according to the proper fitting guidelines of the PPE.

The technique for obtaining the impulse response from these recordings is explained thoroughly by S. Muller and P. Massarani [12] but will be briefly described here. The recorded signals for each azimuth must be individually convolved with the inverse filter of the swept sine signal. The software used to generate the swept sine signal must be able to generate this inverse filter. The result of the convolution is the impulse response. Each impulse response will need to be attenuated so that the signal is less than 0 dBFS; this is a side effect of convolution. Each impulse response must be attenuated by the same amount. The attenuation amount is defined by the attenuation needed for the measurement at 67.5°, because this impulse response should be the loudest. Hence, for all practical purposes make this calculation first. The peak value for this should be attenuated to -6dBFS to allow for head room. Again, the attenuation value defined here should be used for all the impulse responses.

Next, the impulse must be truncated to reduce the reflections of the room and any distortions. This must be conducted by eye. The main impulse response is the largest "spike" appearing in the waveform, see Figure 4A. Any smaller "spikes" appearing before this are distortions and must be removed from the signal. Next, any large "spikes" appearing more than 2 ms after the initial impulse response must also be removed along with the rest of the signal. This is also shown in Figure 4B. The length of all the impulse responses used during this project were 2.38 ms in duration, but may be longer depending on the location of the first reflection. However, the impulse response duration should not exceed 10 ms.

Next the calculation of the ILD, ITD, and TL must be made. This must be done using sophisticated analysis software, such as Matlab. For each of these measurements the signal must be filtered with 1/3 octave filters designed according to the ANSI S1.11-2004 standard [1].

To calculate the TL, the total root-mean-square (RMS) values (dB) of each band of the filtered signal for each of the five PPE measurements must be calculated. The mean of these measurements is then taken for each azimuth. These values are then subtracted from the total RMS values of the measurement taken without any PPE. This should be done for both channels (i.e., the measurement of the right ear for the PPE should be subtracted from the measurement of the right ear without any PPE).

To calculate the transfer function of the PPE for the ILD and ITD, the ILD/ITD of the PPE should be subtracted from the ILD/ITD of the measurement with no PPE. In this way, we can see how the PPE affects these parameters. Note that this is not conducted for the TL, since the TL already uses this method. Examples of TF plots are shown in Section 4.

3.4 PPE Created Noise Test Procedure

To provide a comprehensive and accurate evaluation of the hearing effects of PPE, the noise generated from the fabric as well as mechanical noise must be measured. Only PPE that create noise should be evaluated. This includes powered air-purifying respirators (PAPRs) and PPE that create noise with movement, such as the Rampart Jacket. APRs such as the Millennium APR, do not need to be evaluated if they are not attached to a PAPR because they do not create any noise while head movements are made.

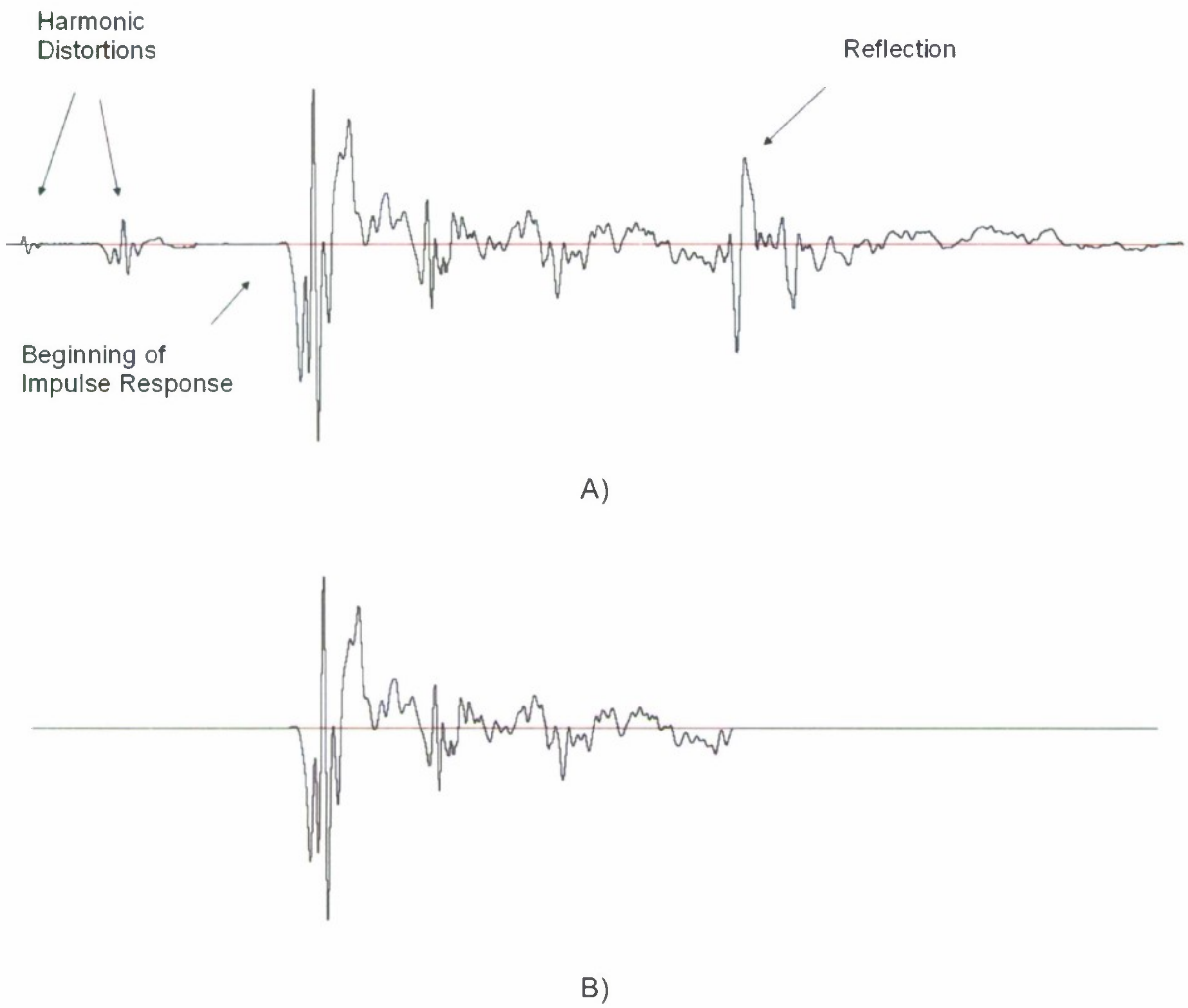


FIGURE 4. A) An example of an impulse response that might be obtained using the Swept Sine method. The actual impulse response occurs at the largest "spike". As shown, there may be smaller "spikes" appearing before (distortions) and after (reflections) the actual impulse response that must be removed. B) Shows the impulse response after truncation. This impulse response is used to calculate the HRTF.

3.4.1 Fabric Noise Procedure

To evaluate the fabric noise generated by PPE, a recording of the noise must be made. This is done for several types of head movements, which are detailed in the Appendix. For this experiment LcT used an actual human subject with a microphone securely placed in each of their ear canals. However, LcT is currently in development of a robotic head and torso simulator, which will replace the need for a human subject. Our developed test method can be easily conducted with either setup, with only minor modifications.

3.4.1.1 Setup and Calibration

All the measurements are calculated at 0° because the noise generated is not dependent on azimuth.

First the recording level must be calibrated so that an accurate recording is obtained. The simulator must be fitted with the PPE. The movement that produces the loudest SPL must be found. While the simulator is performing this movement, the recording level should be adjusted so that the maximum signal level is set to approximately -6 dBFS. The recording level should be used for the duration of the test.

Next, remove the PPE so that a reference SPL can be obtained. This is done by playing pink noise at least 15 dBA above the noise floor for 10 s through a loudspeaker and recording it with the simulator's ears. After the recording is made, the calibration signal must be played again at the exact same level. Using the sound level meter placed at the microphone in one ear, the A weighted SPL should be taken. The SPL in the opposite ear should be within 3 dB of this value. This SPL will be referred to as the *Calibration SPL* and is needed for calibrating the recording level to match the actual SPL heard by the simulator later on. Thus, if the *Calibration SPL* is 80 dB and the average RMS of the recorded signal is -10 dBFS, the recorded fabric noise can then be calibrated to the appropriate SPL (i.e., if the fabric noise has a value that reaches -30 dBFS, we know that this is equal to 60 dB SPL). Before beginning the actual test, all equipment, including the loudspeaker, should be removed to reduce unwanted reflections and noise.

This calibration must be done for each PPE, unless the SPL produced by the loudest movement is similar. If the maximum SPL of a PPE differs by more than 6 dBFS, than a separate calibration must be conducted for that PPE.

3.4.1.2 Procedure

The simulator must don the PPE and perform the selected head movements listed in the Appendix. Each movement should be conducted 8 times at a rate of 50 beats per minute (BPM) and 80 BPM; this will be defined as slow and fast movements, respectively. For a human subject, a monitor with a tempo reference placed as far away as possible can be used. However, the laptop must emit less than 30 dBA of noise, measured at the simulator's ear. LcT used a laptop with a flashing screen to indicate the tempo.

Some of the PPE, as noticed by an LcT employee, were noticed to be uncomfortable if worn for extended periods of time. Thus, if human test subjects are used and the duration of the test is longer than 10 min, then a 5 min break without the PPE worn must be offered to the subject every 10 min.

For each movement, eight recordings will be made. The recording that best represents the movement, in terms of SPL and frequency response should be selected as the final recording to be used. This final selected recording will be used to calculate the speech intelligibility effects of the PPE.

3.4.2 PAPR Noise Procedure

To evaluate the speech intelligibility effects of the noise emitted by PAPRs, a recording of the noise must be made. This is accomplished by placing the PAPR on the

simulator and recording the noise. With the proper calibration techniques, we can then use this noise and determine its effects on speech intelligibility using the STI method.

3.4.2.1 Setup and Calibration

The PAPR noise calibration is conducted exactly as stated in Section 3.4.1.1, with the exception that the maximum SPL level used to calibrate the recording is determined by the SPL of the PAPR while active.

3.4.2.2 Procedure

While the PPE is donned and active, a 15 s recording of the PPE must be made. As with the fabric noise, the proper calibration will allow for the correct SPL, as heard by the simulator, to be mimicked when computing the speech intelligibility effects of the PPE.

3.4.3 Speech Intelligibility Calculation

The speech intelligibility calculation is made using the STI algorithm. The algorithm makes use of the impulse response measurements made in the localization and attenuation test.

For the determination of the speech intelligibility effects while fabric noise or mechanical noise is being generated, the parameters for the STI algorithm are the impulse response of the PPE and the recording of the fabric noise for each movement or mechanical noise. The step to compute the STI score will be explained for one movement type, using the impulse response at 0° and only one speech level, the calculation for any other azimuth, movement type, or speech level is conducted in the same fashion. Obviously the mechanical noise is not a function of movement type, but the calculation is still the same.

Using the 0° impulse response without PPE, determine the gain needed so that the A-weighted total RMS value of the signal is equal to the desired speech level dBA, which will be referred to as the *Speech Gain*. This can be used for any other angle or movement type; however, this value must be recalculated for a different speech level. Next, determine the A-weighted SPL for each octave band frequency from 125 Hz - 8 kHz when the *Speech Gain* is applied to the impulse response of the PPE. These are referred to as the *Speech SPLs*. The next step is to determine the average RMS value of the recorded calibration tone recorded in Section 3.4.1.1. This value is subtracted from the *Calibration SPL* obtained in 3.4.1.1 and is referred to as the *Noise Gain*. The A-weighted SPL for each octave band frequency from 125 Hz - 8 kHz when the *Noise Gain* is applied to the recording of the fabric/mechanical noise is then determined. These are referred to as the *Noise SPLs*. Using the *Speech SPLs, Noise SPLs,* and the impulse response of the PPE, the STI score can be calculated. Use of commercial software that calculates these values, such as Adobe Audition using the Aurora STI plug-in, is highly preferred for those who are not familiar with the STI calculation.

3.5 Environmental Conditions

All the above procedures must be conducted under the same environmental conditions. The room selected to measure the hearing effects of the PPE must be large enough to fit the simulator and loudspeaker, at the specified distance. The room should be acoustically treated to minimize outside noise and reflections. As explained in Section 3.3.2, reflections from the surrounding surfaces in the room can appear in the impulse response measurements.

Though these can be removed through truncation techniques, it is preferable to have a large room with acoustic treatment. This will minimize the level of these reflections and cause them to appear later on in the impulse. All doors should be treated and provide a tight seal from the outside rooms. The measured noise floor should not exceed 35 dBA. The reverberation time of the room should not exceed 500ms.

3.6 Repeatability and PPE Fitting Variance

During the Phase I project, LcT noticed that refitting the PPE and re-conducting the HRTF measurement led to changes in the measured HRTF. In general, the more tangible the PPE is, the greater the variance between measurements. This is also a common problem in hearing protection devices (HPDs) tests, such as the Real Ear Attenuation Test [2]. In these tests, researchers also noticed a difference in outcomes for HPD performance. To overcome this problem, multiple measurements are made and the average of the results is taken. LcT has also decided that this is the best approach to take, since most PPE cannot be fitted the exact same way every time. The designed tests require that every PPE be refitted and tested five times.

An example of the variance expected in the HRTF measurement for the Millennium APR with the Camo Jacket is shown in Figure 5. This PPE was measured four times and the standard deviation for the TL calculation is shown. As expected, the standard deviation is greater at higher frequencies, but is within an acceptable range. Some HPDs in [11] were shown to be as high as 15 dB. By taking several measurements, the standard deviation is reduced and the average effect of the PPE can be calculated.

4. RESULTS

During the Phase I project, LcT obtained multiple pieces of PPE from U.S. Army Reseach, Development and Engineering Command (RDECOM) for testing. The PPE include escape hoods, APRs, PAPRs, helmets, jackets, and chemical suits. In addition to testing each PPE separately (subsystem level), LcT also tested several of the PPE in combination (system level), such as an APR with a jacket. HRTFs (ILDs, ITDs, and TLs) as well as speech intelligibility scores were generated for all of the PPE. Only a few of the results will be shown here for general discussion. An explanation of the meaning of the results will be discussed in Section 5.

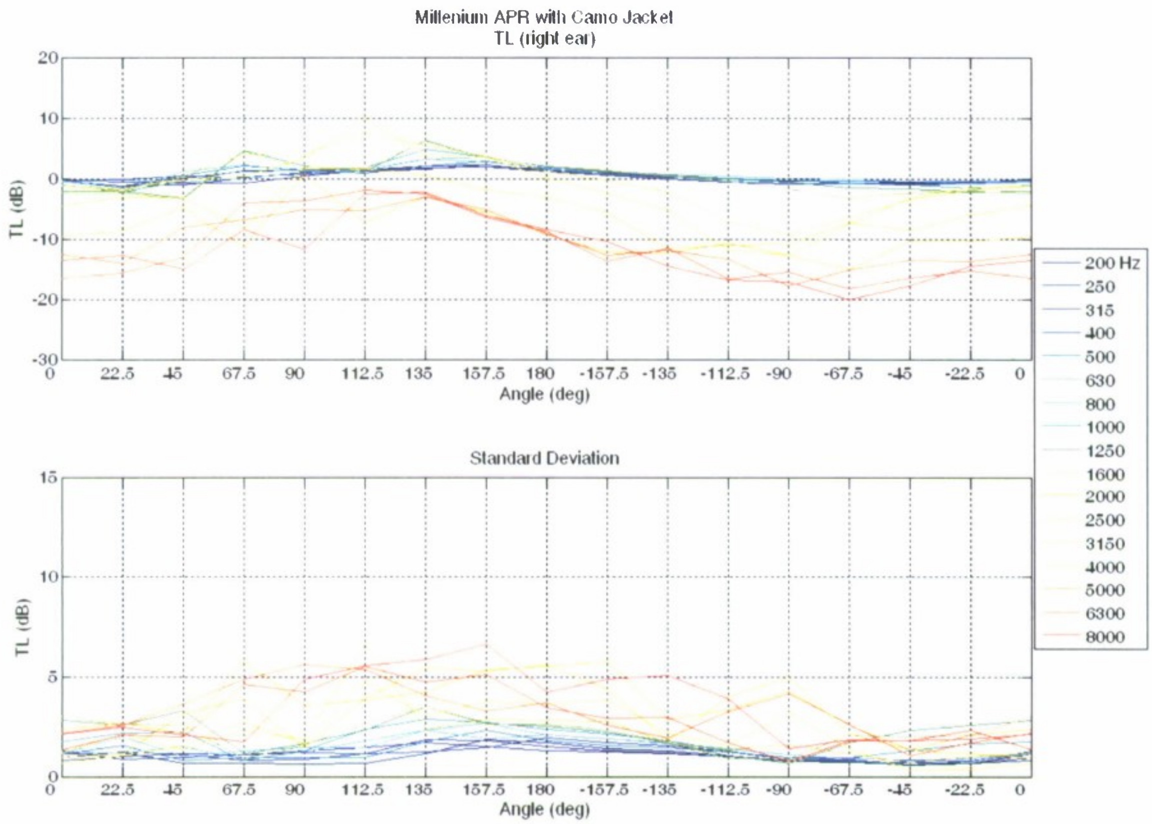


FIGURE 5. The mean outcome for the Transmission Loss (right ear) measurement of the Millennium APR worn with the Camo Jacket. The measurement was conducted five times and the standard deviation between measurements is shown in the lower plot. The standard deviation is within the range of similar tests used to measure the transmission loss of HPDs [11].

A) B)

FIGURE 6. Pictures of the simulator donning the A)Ultra Elite APR and B)Millennium APR with the Camo Jacket. The Ultra Elite PPE does not occlude the ears, but the Millennium PPE with the Chemical suit does.

All the data is plotted in 1/3 octave frequency bands ranging from 250 Hz to 8 kHz. These bands were chosen since they have a similar representation to how the human ear actually analyzes sounds. This also allows us to observe how the PPE affects different frequencies and to make conclusions such as "only the high frequency bands are affected by a given PPE". To keep the discussion simplified, only the plots of the Ultra Elite APR and the Millennium worn with the Camo Jacket will be discussed, as they provide a non-occluded and occluded ear example, respectively. The picture of these two masks can be seen in Figure 6.

4.1 Attenuation Effects

The attenuation effects were obtained by measuring the transmission loss (TL) of the PPE. This is simply the difference in SPL measured without PPE than with PPE. This gives us information on how much the PPE attenuates a given sound. The TL plot for the two PPE is shown in Figure 7.

From our research we have concluded that occlusion of the ear provides the most dramatic change in TL and is most noticeable at higher frequency bands (> 2 kHz). The reason that only the high frequency bands are affected is due to the fact that all of the PPE are not thick enough or large enough to diffract low frequency signals, which have large wavelengths. For instance, a 1 kHz wave has an approximate wavelength of 34 cm and a 250 Hz wave as an approximate wavelength of 1.37 m. Again, these large wavelengths cannot be sufficiently attenuated by the tested PPE, as shown in Figure 8.

All of the APRs tested that did not occlude the ears, showed little to no attenuation across all frequency bands as seen with the Ultra Elite PPE. Most of the PPE that did occlude the ears did show significant attenuation (>15 dB) at frequency bands above 2 kHz, especially when one of the ears is pointed directly at the sound source, as shown above.

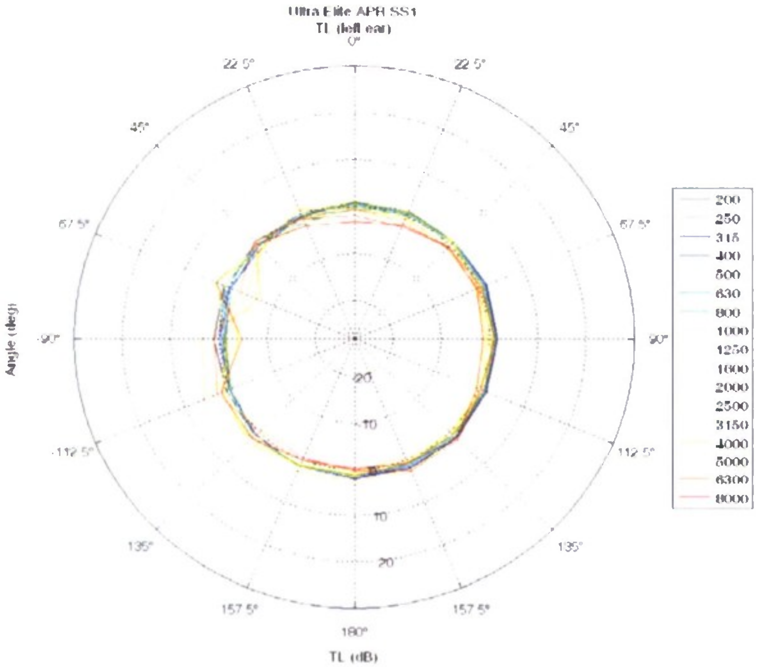
4.2 Interaural Level Differences

The interaural level differences give important information to the auditory system to the location of sound sources. Thus, if these are disturbed, a shift in the perceived location of the sound source can occur. A more detailed explanation on how these shifts alter the perceived sound source location is given in Section 5.1.1. The effect of the two PPE on the ILDs is shown in Figure 8.

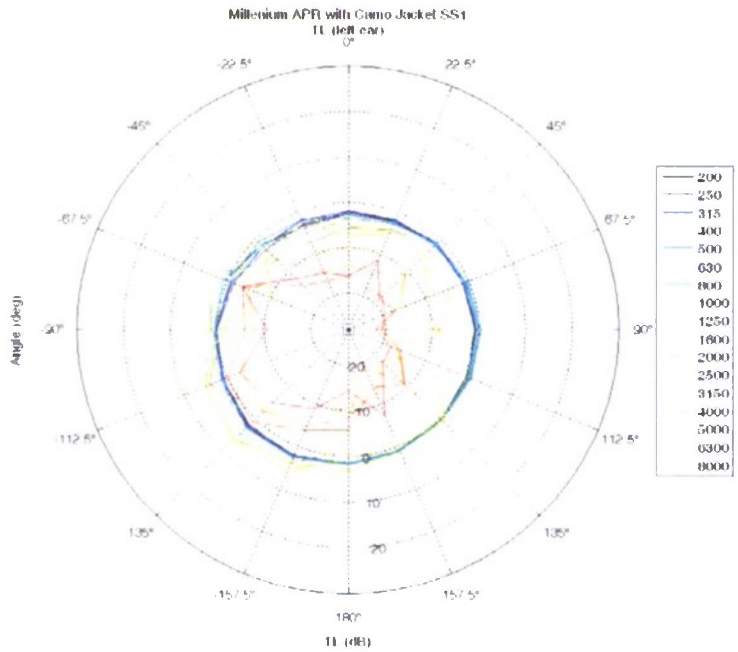
As with the TL plots, only PPE that occludes the ears were observed to have a significant impact on the ILDs. In Figure 8B, we can see a large change in the ILDs, especially as the ear is pointed closer to the sound source (±67.5° to ±112.5°). As with the TL findings, PPE that did not occlude the ear followed a similar pattern to Figure 8A, whereas PPE that did occlude the ear closely resembled Figure 8B.

4.3 Interaural Time Differences

For the ITDs, most research has shown that these cues are most important for low frequency content. Therefore, only the 1/3 octave bands from 200 Hz to 1250 Hz are shown. As with ILDs, the ITDs give important information to humans on the perceived location of a sound source. The effect of the PPE on the ITDs is shown in Figure 9.

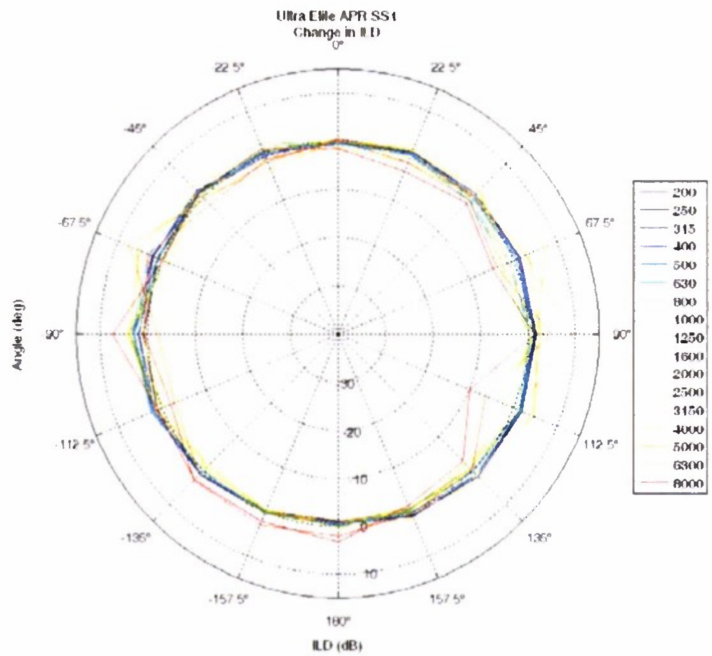


A)

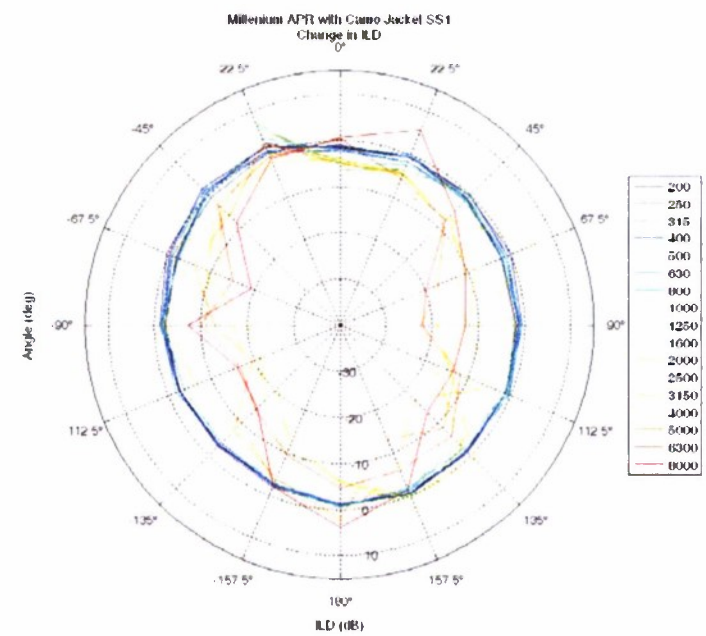


B)

FIGURE 7. The attenuation effects (only left ear shown) of the A) Ultra Elite APR and B) the Millennium APR with the Camo Jacket PPE. As shown, the non ear-occluding PPE in A) has minimal attenuation effects, but the ear-occluding PPE in B) has a significant effect, especially as the sound source is directly to the left/right of the listener. The graph is plotted for 1/3 octave frequencies from 200 Hz to 8 kHz. Darker colors represent the low frequency bands and the lighter colors represent the higher frequency bands. The attenuation of the PPE increases as the data moves toward the middle of the plot.

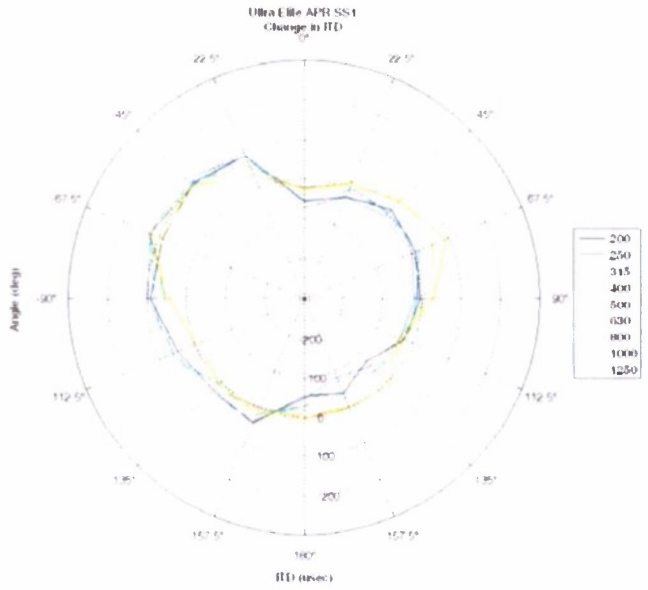


A)

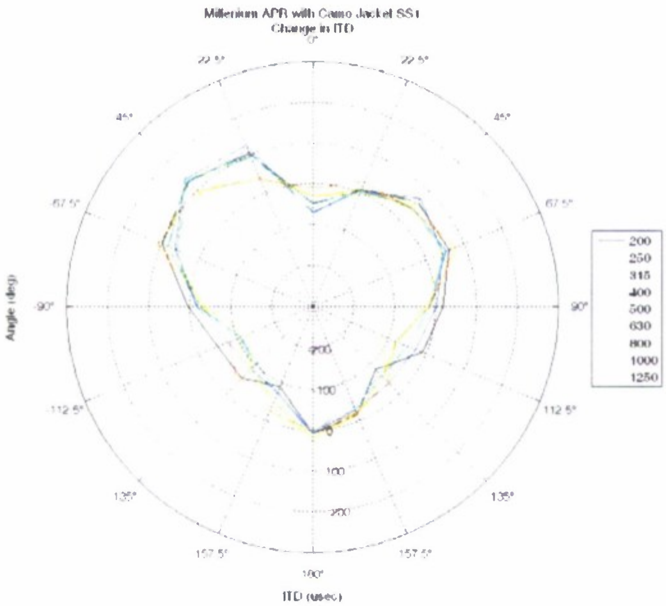


B)

FIGURE 8. The effects of the A) Ultra Elite APR and B) the Millennium APR with the Camo Jacket PPE on the interaural level differences. As shown, the non ear-occluding PPE in A) has minimal effect on the ILD, but the ear-occluding PPE in B) has a significant effect especially as the sound source is directly to the left/right of the listener. The graph is plotted for 1/3 octave frequencies from 200 Hz to 8 kHz. Darker colors represent the low frequency bands and the lighter colors represent the higher frequency bands. As the data moves toward the middle of the plot, the ILD between the ears is reduced.



A)



B)

FIGURE 9. The ITD effects of the A) Ultra Elite APR and B) the Millennium APR with the Camo Jacket PPE. As shown, both PPE have similar effects. The ITDs at most azimuths are altered by less than 100 μsec. The graph is plotted for 1/3 octave frequencies from 200 Hz to 1250 Hz. Darker colors represent the low frequency bands and the lighter colors represent the higher frequency bands. The negative data (closer to center) can be interpreted as reducing the ITD and the positive data (closer to edge) can be interpreted as increasing the ITD.

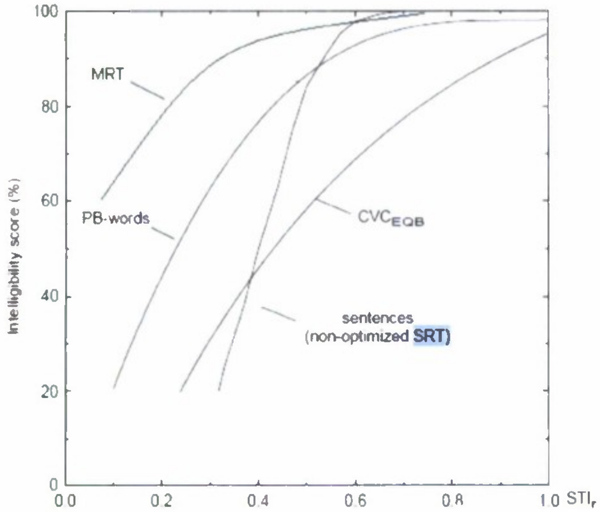
Both PPE provide a disturbance in the ITDs. Note that the scale is in microseconds. Most research done with ITDs have shown that a change between 20-100 µsec will result in a just noticeable change in the perceived location of the sound source. It is important to note that the sampling rate of our recorded impulse responses was set at 44.1 kHz, thus giving us a time resolution of approximately 22.7 µsec. As explained in a previous publication [10], ITD calculations can have an error within a few samples. For example, if the ITD calculation had a 2 sample error this would correspond to approximately 44.4 µsec, which is in the range of a just noticeable difference. To overcome this error, LcT will explore more sophisticated ITD calculation methods that can provide subsample resolution and/or increase the required sampling rate of the system. From the plots above we can see that for most azimuths the change in ITDs is within the just noticeable range for both PPE. However, in some of the escape hoods tested the change in ITDs is well outside of this range for certain azimuths, which can cause a change in localization performance for users donning this PPE. More will be explained on the psychoacoustic effects of these changes in Section 5.1.1.

4.4 Speech Intelligibility

The speech intelligibility effects are presented in several ways. All of them make use of the well-known Speech Transmission Index [16,17], which is used to predict the intelligibility of speech under various conditions. To better understand how the Speech Transmission Index (STI) relates to the actual ability of humans to understand speech, a chart showing the correlation between the STI and word accuracy of several different wordlists are shown in Figure 10A. These are the Modified Rhyme Test (MRT), Phonetically Balanced (PB), Consonant-Vowel-Consonant (CVC), and Speech Reception Threshold (SRT) wordlists. From this figure, we can see that some wordlists are more difficult than others in terms of word recognition. Therefore, in the STI plots below, the STI score is compared to several of these wordlists. Because the intelligibility of speech also depends on the SPL of the talker's speech, a table of common speech SPLs is given in Figure 10B. It will be shown that for some PPE, speech can be intelligible at whispering speech SPLs. However, for some, PPE speech does not become intelligible until the talker speaks at shouting levels. This emphasizes the importance of defining a comprehensive grading system that can take into account the common environmental conditions where a given PPE will be used, as explained in Section 2.1.2.

The LcT was given two PAPRs to evaluate during the Phase I project. These were the Scape escape hood and the Responder PAPR. Due to time limitations, the Responder PAPR was only evaluated with the Ultra Elite Gas Mask, but similar results can be expected with similar PPE (i.e., Avon C50, Millennium, and the FR-M40-20 masks). The Scape PAPR was observed to produce the most amount of noise with an SPL of 80 dBA while the Responder PAPR produced noise around 60 dBA. The results of the STI for various speech levels for the Ultra Elite Mask are shown in Figure 11.

As expected, the PPE is very detrimental to speech intelligibility. By looking at the STI reference chart in Figure 10A, we can see that a person donning this mask would have trouble understanding low to normal speech levels, while active. For example, the speech heard at the listeners ears would have to be near 57 dBA for 85% of the words to be understood (PB wordlist).



Type of Speech	*SPL (dBA)*
Whisper	20
Quiet Conversation	30
Normal Conversation	60
Shouting	80

A) B)

FIGURE 10. A) Reference to STI score translations[16]. Thus, an STI rating of 0.5 is necessary for about 85% of the words in the PB word list to be recognized. B) Reference to common speech loudness levels. These two figures can be used to interpret the STI scores in the figures below.

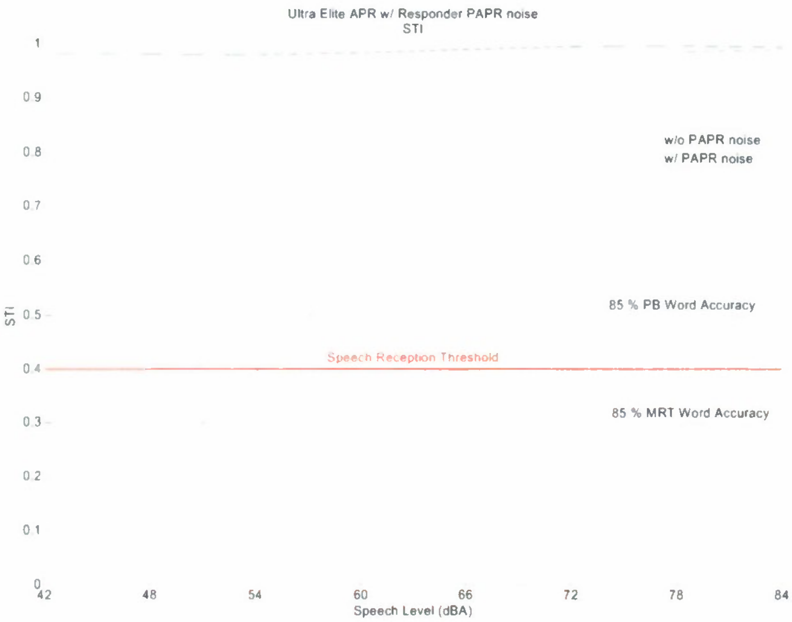


FIGURE 11. The STI score for the Ultra Elite Mask with the Responder PAPR. The green line shows the score while the PAPR is active and the blue line gives the STI score without the PAPR active. From the plots in Figure 10A, we can interpret these results in terms of word accuracy. Thus, the red solid line is the SRT (50% word accuracy using SRT wordlist) and the black dashed lines above and below this represent where a word accuracy of 85% is achievable for the PB and MRT wordlist, respectively.

For the evaluation of fabric noise, LcT tested several different head movements at two speeds. The head movements and speeds are given in the Appendix. LcT also chose to evaluate the STI score with respect to time, as well as speech level. A more detailed explanation of these choices is given in Section 5.1.2. The STI results for the Millennium APR with the Camo Jacket while performing a "fast" head rotation to the left is shown in Figure 12A. The two dips in the STI score correspond to the movement of the head rotating to the left and rotating back to the centered position, respectively. Though not necessary, a plot showing how the measured SPL changes over time can also be plotted, as shown in Figure 12B. This allows us to see how loud the movement actually is perceived by humans (using an A-weighted scale) and at what point in the movement the loudest SPLs occur.

From Figure 12A, we can see that the fabric noise can significantly reduce speech intelligibility scores even at moderate talking levels. For the Camo Jacket, this effect was observed for most of the movements. The effect was even greater for the TyChem SL Chemical Suit. This is most likely due to the tangible plastic material of the suit that has the ability to crinkle and produce lots of noise. From Figure 12B we can see that noise levels between 40 and 50 dBA are being generated by this movement, which is most certainly loud enough to disrupt speech intelligibility at moderate talking levels and below. Similar results were also attained for the JSCESM Escape Hood.

For PPE that does not generate fabric or mechanical noise, a different evaluation must be conducted. We would expect that ear occluding PPE would affect speech intelligibility in some way. Therefore, a test to determine the lowest level of speech that can be understood, known as the Speech Reception Threshold (SRT), is used. This is essentially the level of speech in which 50% of the words are understandable and is explained further in Section 5.1.2. The STI score for the Millennium APR with the Camo Jacket, while not producing any PPE created noise is shown in Figure 13. The SRT, according to the SRT (non-optimized) sentences in Figure 10A, is also plotted (red line). The 85% word accuracy STI score according to the PB and MRT wordlist are also shown for reference. A reference to the STI score without any PPE is also shown.

The Millennium APR with the Camo Jacket is shown to raise the SRT by approximately 4 dBA. This plot again illustrates the need to incorporate HCT into the evaluation of PPE. From the plot we can see that the performance of the Millennium APR with the Camo Jacket at low speech levels is reduced slightly compared to the no PPE case. However, at normal speech levels this PPE has little effect on speech intelligibility.

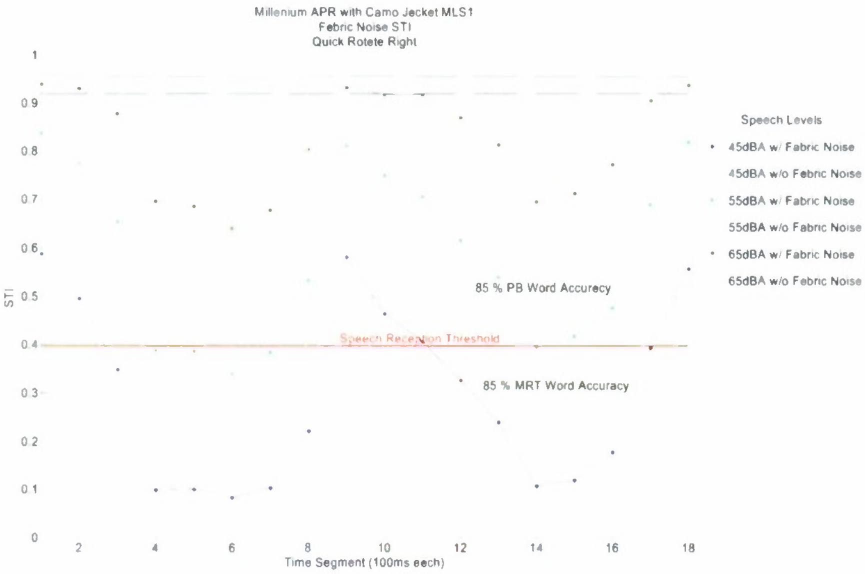
5. ANALYSIS OF RESULTS

In this section, we will provide a psychoacoustic analysis of the results obtained from our tests. The analysis will consist of the perceived localization and speech intelligibility effects of the PPE. An explanation of the developed prediction models is also given.

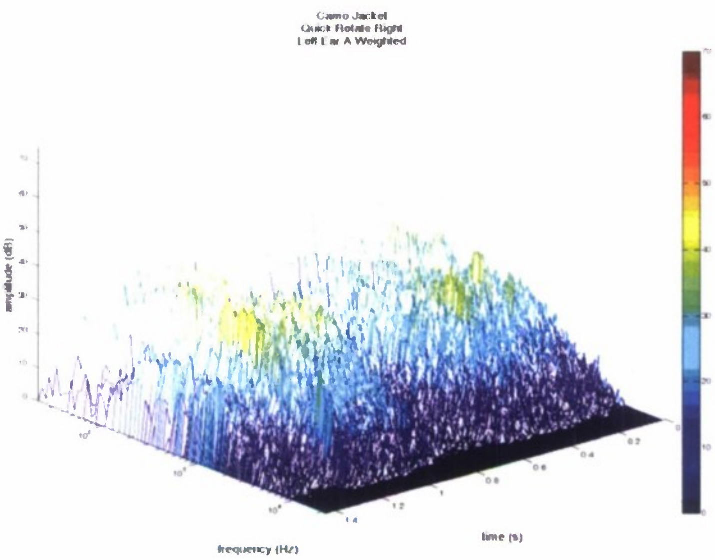
5.1 Psychoacoustic Analysis

The LcT has developed effective tests to evaluate the localization and speech intelligibility effects of PPE. The LcT has also shown the results of these tests for various PPE. The next step is to analyze these results and provide a grading system to evaluate the results of the developed test methods. However, before this can be done, we must first understand how the effects of the PPE affect the ability of a person to localize sounds and understand speech. In

this way we can determine how much change is acceptable before localization or speech intelligibility is compromised.



A)



B)

FIGURE 12. A) The STI score for the Millennium APR with the Camo Jacket while performing a fast head rotation to the left. The solid blue, cyan, and green lines show the STI scores for various speech levels while performing the movement. The dotted lines show the STI scores while no movement is performed. The red solid line shows the SRT. In this way, we can see how the head movement affects speech intelligibility. The dips in the STI score correspond to the increasing SPL while the movement is being performed, as shown in B). B) A waterfall plot of the generated SPL while performing the movement with respect to time and frequency. The movement consists of rotating the head to the left and then back to the centered position, thus the reason for two "peaks" in the above plots.

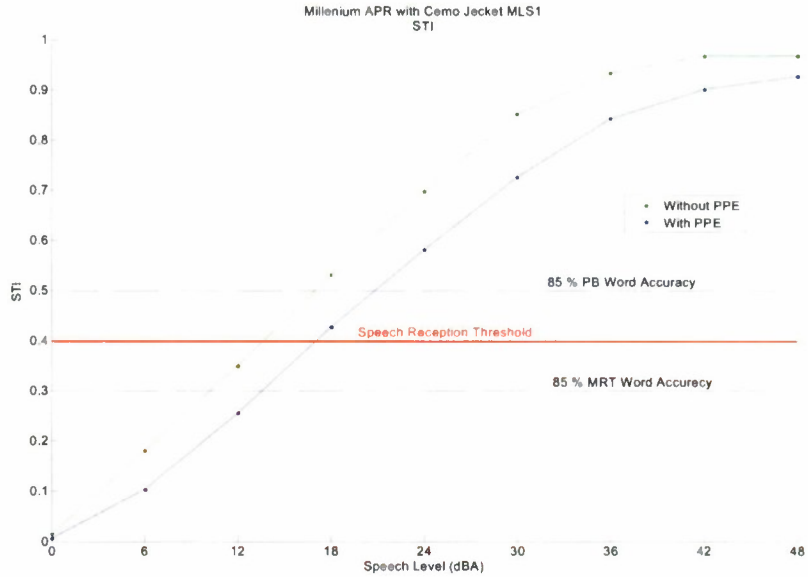


FIGURE 13. The STI score for the Millennium APR with the Camo Jacket with no noise present. Here we can see that at low speech levels the SRT for this PPE increases slightly. The green line is the STI score without any PPE being worn and the blue line shows the STI score while the PPE is worn. The red solid line is the SRT (50% word accuracy using SRT wordlist) and the black dashed lines above and below this represent where a word accuracy of 85% is achievable for the PB and MRT wordlist, respectively.

5.1.1 Localization Effects

As mentioned in Section 2.1.3, humans localize sound sources through the ITD, ILD, and TL of the source. Unfortunately, the role and importance of each of these cues are still in debate as to which cues determine the localization of sound sources. In general, the ITDs are more important at signals with frequency content below 1500 Hz whereas the ILDs and spectral cues are more important above 1500 Hz [4, pp 137-177]. However, some research has shown that all of these cues are utilized across the entire hearing spectrum.

In some research studies, the minimum change in ITD or ILD needed to alter the perceived location of a sound source has been determined and is referred to as the just noticeable difference (JND) [21]. This is a function of horizontal location (azimuth) and is on the order of 1dB for ILDs and between 20-100 μsec for ITDs. These JNDs refer to a 2-10° shift of the sound source, again depending on the horizontal location; this is referred to as localization blur. No research, to LcT's knowledge, has examined the effects of large differences in interaural cues, which are evident in the results of some of the PPE tested by LcT. Therefore, it is difficult to predict by how much the PPE will shift the perceived location of the sound source, but we do know, however, that it will change. Not only is this a problem, but another parameter that must be taken into account is the acceptable amount of localization error. Again, this is also a function of the environment where the PPE will be used. For example, in an environment where visual cues may be absent (i.e., a dark room), a person may rely more heavily on the

auditory information to locate a sound source, thus a localization error greater than 10% may not be acceptable. However, in a well lit, low-risk environment, a higher localization error may be acceptable.

Some human subject localization experiments have been conducted while wearing PPE or hearing protective devices (HPDs), such as earplugs, but again none have correlated the changes in TLs, ILDs and ITDs with localization effects. Most research conducted in this area is in agreement with the conclusion that the main effect of PPE is the increase in front-to-back confusions when localizing sound sources [5, 9, 18, 19]. For example, a sound source at 45° can appear at 135° (with 0° equal to facing the sound source). This is believed to be due to the attenuation of high frequency content that is vital for differentiating between front-to-back localization as explained in Section 2.1.3. This is in agreement with our findings, where PPE that does significantly attenuate the high frequency content (above 1 kHz) results in increased front-to-back confusions as noticed in an experimental test with an LcT employee. Our TL calculations are an effective tool for assessing high frequency attenuations. Therefore, one goal of the Phase II project will be to determine how much high frequency attenuation is acceptable before a significant increase in front-to-back confusions occur.

Another localization study was conducted using earmuffs and earplugs and the mean horizontal error was increased by < 10°, but again the most significant impact was an increase in front-to-back confusions (approx 25% increase) [9]. LcT hypothesizes that ear-occluding PPE will behave in a similar manner. This may be acceptable in some scenarios, but not in others, as explained above.

The Kevlar helmet that is similar to our ACH helmet was tested [19], which allows us to compare our tests with actual human localization experiments. The Kevlar helmet was shown not to increase front-to-back confusions or localization error significantly for a low frequency dominant sound source (M16 cocking stimulus) and this is in good agreement with our ITD (low frequency cue) and TL (front-to-back confusion cue) data that shows minimal changes. This is shown in Figure 14 where the change in ITDs is below 100 μsec and most of the TLs are below 5 dB. Thus, LcT believes a correlation between our ITD, ILD, and TL data can be made to determine the effect of PPE on localization error.

In conclusion, LcT is in agreement with other research that concludes that most of the localization errors will be front-to-back confusions caused by the high frequency attenuation. Because there is no conclusive research correlating localization error caused by ILD, ITD, and TL changes, LcT will propose to conduct some human subject localization experiments for several of the PPE to correlate the results of the developed tests to the actual perception of humans. LcT hypothesizes that by conducting such experiments, they will be able to determine how the changes in the HRTF of humans donning PPE will disrupt localization, thereby allowing LcT to provide an accurate and effective grading system for the localization effects of PPE. These experiments will also be necessary to validate our developed tests, before incorporating the tests into a standard.

5.1.2 Speech Intelligibility Effects

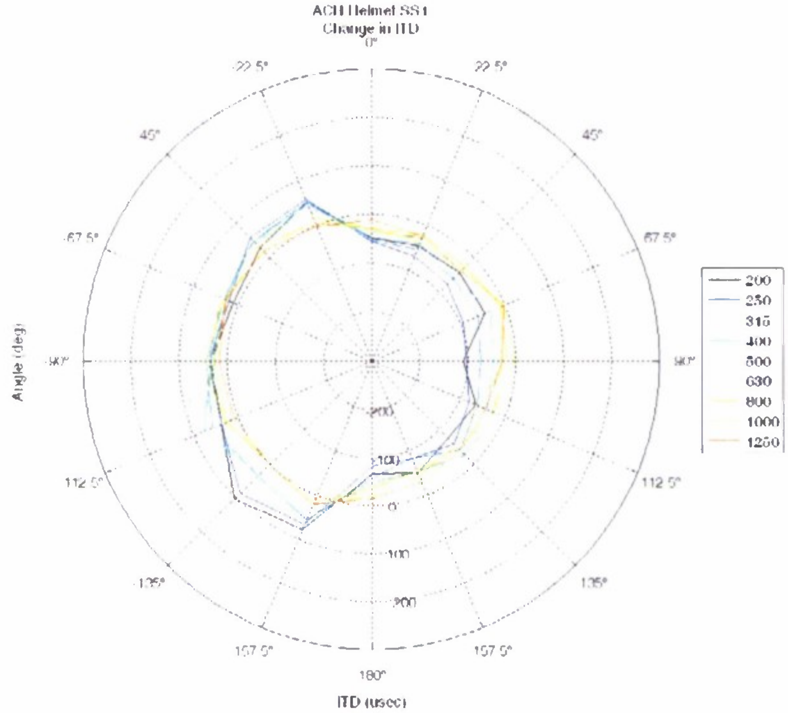
The speech intelligibility effects of PPE and PPE created noise have been effectively assessed by LcT using the STI algorithm. The STI allows us to predict the speech intelligibility under various conditions. LcT has shown that fabric noise and mechanical noise from PAPRs can severely attenuate speech intelligibility in certain situations. Again, it is important to note that speech intelligibility is dependent on the loudness of the talker's voice.

This aspect must be taken into account when defining acceptable speech intelligibility limits for a standardized test. Therefore, during Phase II of this project, it will be necessary for LcT to discuss with RDECOM in what situations these PPE will be used. For instance, if the PPE will be used in scenarios where people may whisper or talk softly (< 40 dBA SPL), as in stealth operations, a more strict criteria will be needed for speech intelligibility effects. Also, it will be important to determine what word accuracy rate is acceptable for a PPE to have a passing score for our test methods. For example, the NOISH MRT standard indicates that a performance rating of 70% is required for a PPE to pass their speech intelligibility test for a speaker with speech levels between 75 and 85 dBA. Clearly this complicates the study and a balance of HCT's and a grade must be found.

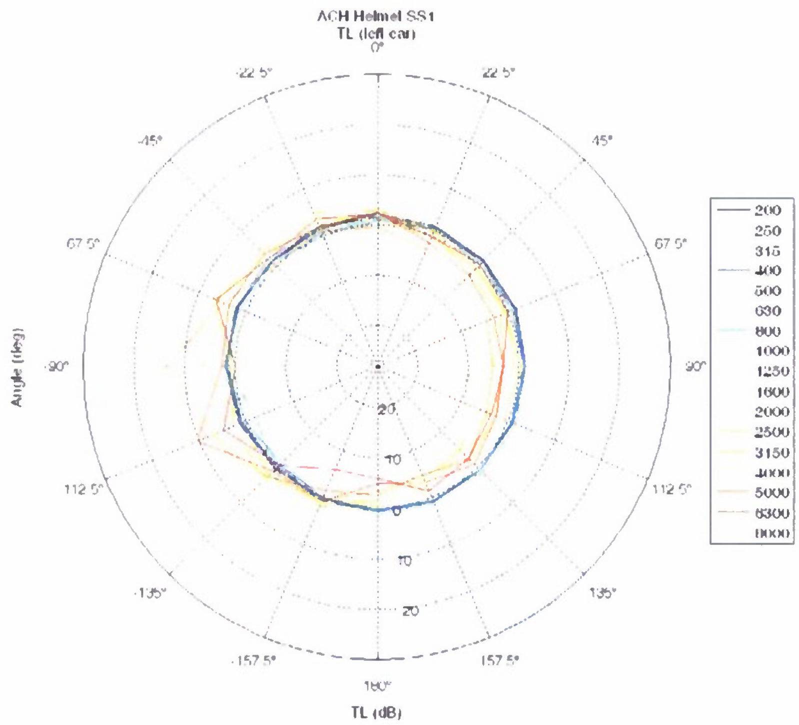
Some PPE do not create mechanical or fabric noise loud enough to affect speech intelligibility, but they can still affect speech intelligibility. As stated in Section 2.1.4, the SNR is the most significant factor in determining speech intelligibility. When PPE is worn, the SNR will remain the same, whereas, the PPE will attenuate the speech and noise equally, unless the PPE attenuates the speech below the threshold of hearing, thereby decreasing the effective SNR. The threshold of a person's ability to understand speech is often measured using the Speech Reception Threshold (SRT). This is the SPL at which 50% of the speech is understood correctly. The STI algorithm also allows us to predict this threshold, converting the STI score into the predicted word accuracy percentage. Thus, the point where the STI score correlates with a 50% word accuracy score (i.e., STI of 0.4 for the SRT wordlist, see Figure 10A) is the SRT. Using this metric we can determine how PPE that does generate PPE created noise will affect the SRT.

For PPE that does generate mechanical noise, such as the Ultra Elite APR with the Responder PAPR, the STI calculation allows us to determine how much speech intelligibility is reduced. This was shown in Figure 11. Using this metric we can determine acceptable levels of mechanical noise, which is one goal of the Phase II project.

For the assessment of fabric noise an important psychoacoustic effect to take into account is the duration of the noise. The STI algorithm assumes that the noise is stationary. The plot of the fabric noise with SPL over time in Figure 12 shows that this is not true for fabric noise. However, the duration of the movement can last over several hundred milliseconds, thus the noise can be thought of as stationary over small time periods. The time period shown in the STI fabric noise plots in Section 4.4 is 100 ms. This time was chosen because it is similar to the average speaker's syllable/second rate, which ranges from five to eight syllables/second depending on the speech rate of the talker [7]. Thus, we can expect the fabric noise to affect speech intelligibility on a syllable level, if not a word level. However, more research needs to be conducted to better understand how quick duration noises can affect speech intelligibility.



A)



B)

FIGURE 14. Changes in A) ITDs and B) TLs for the ACH helmet. As shown, there is little to no change in each of these plots, which would indicate that this PPE has minimal effect on localization performance. This is in good agreement with the Kevlar helmet tested with human subjects in [19].

5.2 Prediction Model

A prediction model was also developed based on our findings to predict the effects of PPE. The model developed by LcT was generalized to model the effect of APRs, escape hoods, jackets, helmets, and chemical suits. LcT has made RDECOM aware that for a comprehensive mathematical model to be developed, more PPE and acoustic material property characterization would be needed. The attenuation effects of the PPE are thought to be directly related to the PPE material stiffness and the acoustic flanking paths into the mask [3]. If a more comprehensive prediction model is needed, LcT can investigate these findings more thoroughly in the Phase II project.

The prediction models generated by LcT can be seen as the expected effect of an APR, escape hood, etc. on the HRTF. These prediction models can be used to assess PPE that has not yet been tested by the developed test methods. An example of the prediction model for the effect of a Jacket is shown in Figure 15. Thus, from 15A we can assume that by wearing a Jacket, the high frequency content will be attenuated as much as 20 dB, most notable when the sound source is to the left/right of the person. Figure 15C also shows the same results for the ILDs. The ITDs, however, show only about a 50 μsec change at a few azimuths. All the plots also give the standard deviation of the model when tested against individual PPE. As shown, most of the standard deviations for each frequency are below 5 dB for TLs and ILDs and within 60 μsec for ITDs. These deviations are tolerable and expected due to the variability of fitting PPE, as explained in Section 3.6. These models give insight on how these important parameters, which determine localization and speech intelligibility, are affected when a human dons a given PPE.

6. CONCLUSION

During the Phase I project, LcT has successfully developed the necessary test methods to quantify the localization and speech intelligibility effects of PPE. This includes incorporating the noise generated by PPE, such as fabric and mechanical noise. LcT has specified the necessary equipment and room conditions necessary to conduct the developed tests. The test methods make use of a head and torso simulator and incorporate advanced DSP techniques and algorithms to evaluate the PPE. This effectively removes the need for human test subjects, thereby making the developed tests easy to implement and less costly. However, the tests can easily be extended to be used with a human test subject instead of a head and torso simulator. A detailed explanation of the developed tests was given in Section 4.

To evaluate the speech intelligibility effects of PPE, the Speech Transmission Index (STI) was used. This method has been shown to effectively predict the speech intelligibility under various conditions. The STI was used to evaluate the speech intelligibility effects of fabric noise created by head movements, as well as mechanical noise generated by PAPRs. These noises were observed to greatly affect speech intelligibility under certain conditions.

The localization effects of PPE were evaluated by obtaining the HRTF of the simulator while donning PPE. The transfer function (PPE effect) was obtained by comparing the HRTF with PPE and without PPE. This allowed us to observe the actual hearing effects of the PPE. The HRTF provides the necessary cues to determine the localization effects of PPE. The next step in analyzing these effects is to correlate the PPE effects with actual human

localization experiments. LcT will propose to conduct these experiments during the Phase II project. By doing so, LcT will be able to effectively correlate the HRTF effects while donning PPE to the perceived localization effects for an actual human subject. Therefore, any PPE will be able to be accurately evaluated without having to be tested by actual human subjects.

Prediction models for PPE were also developed during Phase I. These models provide a generalized evaluation for the expected effects of the PPE. These can be used to determine the effects of PPE that have not been evaluated. The prediction models were generated by categorizing the PPE LcT currently has into five groups: APRs, Escape Hoods, Helmets, Jackets, and Chemical Suits. A more comprehensive model may be developed during Phase II of this project that will include the noise parameters and acoustical parameters of the PPE.

In conclusion, LcT has developed the necessary test methods to accurately assess the hearing effects of PPE. However, more research needs to be conducted to determine the significance of these effects and to develop a grading system that will allow users to easily assess PPE in terms of hearing. The developed test methods will give insight to PPE manufacturers on how to develop PPE that will allow for accurate communication and localization. The primary goal of Phase II of this project will be to further refine the test methods and incorporate them into an existing standardized test.

7. PHASE II PLAN

The Phase II project will focus on further development of the test methods with the goal of producing a standardized test to effectively evaluate the hearing effects of PPE. Before a set of standardized tests can be developed, further research on the psychoacoustic effects of PPE must be conducted. In addition to this, the developed test methods need to be further refined. This includes the purchasing of new equipment to help further automate the testing procedure and provide more accurate results. This also means defining a grading system to characterize the hearing performance of PPE for the improved standardized tests.

As stated in Section 5.1.1, we have developed the necessary methods to quantify the effects of PPE, but there is currently not enough information on how these effects are perceived by humans. Further research, which may include conducting hearing and localization experiments with human test subjects, is needed to solve this problem.

A list of possible Phase II project tasks is given below:

- Refine the head and torso simulator. This includes purchasing artificial ear simulators for the simulator to allow a more accurate representation of a human. This also includes using an automated turntable system to rotate the simulator in the horizontal plane. This will reduce human error caused by manually rotating the table. In another research project at LcT, a robotic head and torso simulator is being developed that can also be used for this project. This will remove the need for human test subjects for recording the fabric noise generated by PPE.

- Develop a grading system to provide a rating for PPE. A grading system will allow users to understand the hearing effects of the PPE using a simplified metric performance. This will allow them to know whether or not a given PPE should be used for a hearing critical task (HCT).

- Incorporate HCT parameters into the grading system. This will allow a weighted grading system for PPE dependent upon the type of task. A list of HCT parameters will need to be developed.

- Determine the acceptable amount of PPE created noise and hearing attenuation allowable for PPE designs. This can be incorporated into the standardized test and give PPE manufacturers guidance on future PPE design.

- Expand the tests to include the vertical localization effects of the PPE as well. This may be useful in some HCTs where localizing sound sources above or below is important.

- Develop automated software to assist users in conducting the developed tests. The software will allow for control of the automated turntable thereby making a majority of the testing procedure automated. The software will also compute all the necessary calculations (ITDs, ILDs, etc.) and produce a grade for PPE that is tested. To analyze the results of the developed tests requires advanced digital signal processing (DSP) techniques and thus requires a background in engineering and DSP to conduct the tests. Companion software can allow for novice users to conduct the tests.

- Further develop the environmental requirements to conduct the tests. This may also include the development of a portable testing environment that can easily be transported and set up with minimal effort.

- Further research the psychoacoustic effects of PPE. We have shown that PPE can alter the HRTF, but a determination on how this actually affects the perceived hearing ability of humans needs to be made. This may include conducting human subject tests.

- Further refine our developed algorithms and prediction models.

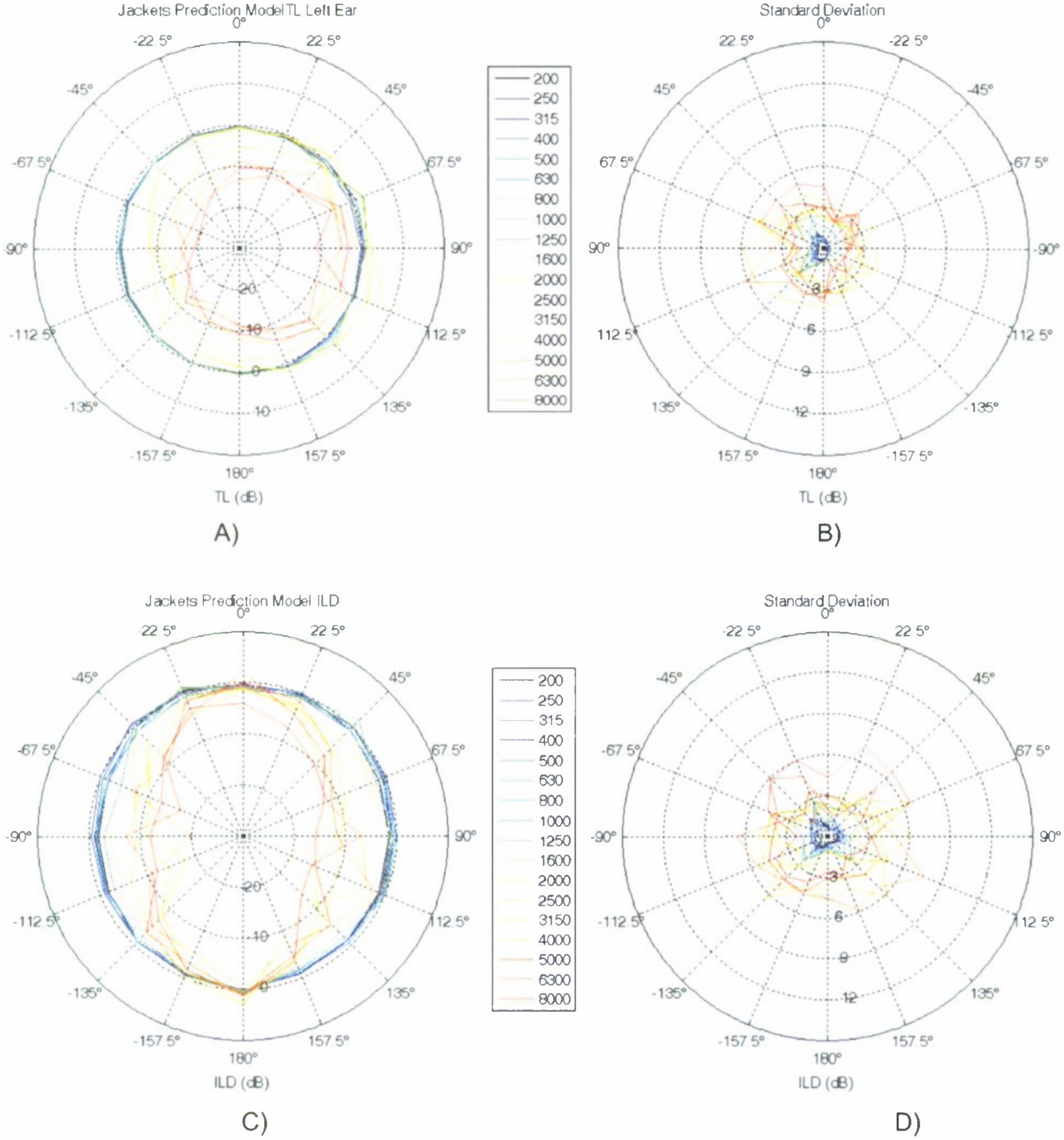
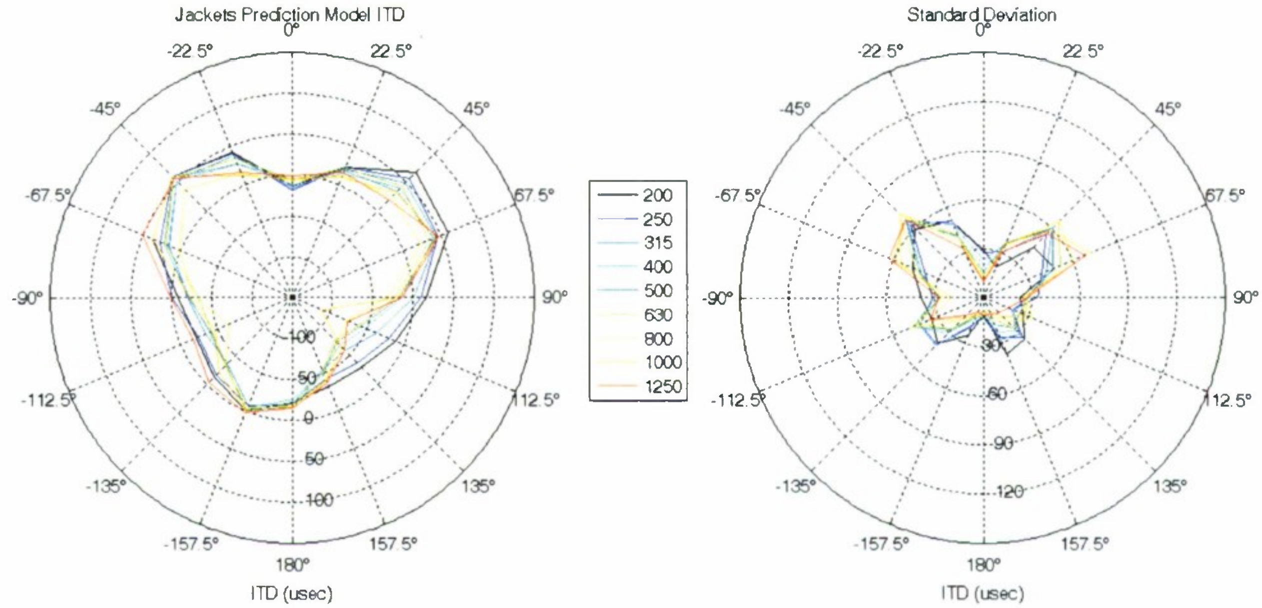


FIGURE 15. A) The model to predict the attenuation by donning a Jacket (only left ear shown).B) The standard deviation of the model when compared to the individual testing of each Jacket. From this model we estimate the expected attenuation in SPL when a user dons similar PPE. The prediction of the effects of the C) ILDs and E) ITDs are also given along with their standard deviations in D) and F), respectively.



E) F)

FIGURE 15. A) The model to predict the attenuation by donning a Jacket (only left ear shown).B) The standard deviation of the model when compared to the individual testing of each Jacket. From this model we estimate the expected attenuation in SPL when a user dons similar PPE. The prediction of the effects of the C) ILDs and E) ITDs are also given along with their standard deviations in D) and F), respectively. (Continued)

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APPENDIX

FABRIC NOISE TEST MOVEMENTS AND SPEEDS

The below movements must be performed at a rate of 50 beats per minute (BPM) and 80 BPM:

Movement Name	Movement Description
Rotate Head Left	Standing still, the subject must rotate their head from the center position to the left most position, as to look left, and then rotate back to the center position.
Rotate Head Right	Standing still, the subject must rotate their head from the center position to the right most position, as to look right, and then rotate back to the center position.
Full Head Rotation	Standing still, the subject must rotate their head from the center position to the left most position, as to look left, rotate back to the center position, then to the right most position, as to look right, and then rotate back to the center position.
Tilt Head Forward	Standing still, the subject must move their head from the center position to the forward most position, as to look down, and then move back to the center position.
Tilt Head Backwards	Standing still, the subject must move their head from the center position to the backward most position, as to look up, and then move back to the center position.
Full Head Tilt	Standing still, the subject must move their head from the center position to the forward most position, as to look down, move back to the center position, then to the backward most position, as to look up, and then move back to the center position.
Flex Head Left	Standing still, the subject must move their head from the center position to the leftmost position, as to touch the left ear to the left shoulder, and then move back to the center position.
Flex Head Right	Standing still, the subject must move their head from the center position to the rightmost position, as to touch the right ear to the right shoulder, and then move back to the center position.
Full Head Flex	Standing still, the subject must move their head from the center position to the leftmost position, as to touch the left ear to the left shoulder, move back to the center position, then to the rightmost position, as to touch the right ear to the right shoulder, and then move back to the center position.

Roll Head Right	Standing still, the subject must roll their head from the forward most position, as to look down, to the left most position, as to touch the left ear to the left shoulder, roll to the backward most position, as to look up, roll back to the leftmost position and then roll to the forward most position.
Roll Head Left	Standing still, the subject must roll their head from the forward most position, as to look down, to the right most position, as to touch the right ear to the right shoulder, roll to the backward most position, as to look up, roll back to the rightmost position and then roll to the forward most position.
Open Mouth	Standing still, the subject most open their mouth and jaw from the closed position to the fully open position and then return to the closed position.